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1 Purpose

The search for extrasolar planets—planets orbiting stars outside our solar system—is motivated by the desire to discover small planets similar to Earth. Since small planets are difficult to detect, the first step is finding giant planets with large orbits, like Jupiter. Solar systems containing these planets may have smaller, Earth-like planets travelling closer to the parent star. However, current methods detect extrasolar planets indirectly by observing a planet's gravitational influence on its parent star. These methods are primarily sensitive to giant planets with small orbits. A new method is needed to directly observe planets with large orbits. Direct observation can also provide additional information about a planet's composition and/or orbit.

Directly observing an extrasolar planet from Earth is challenging because of the relative proximity of the planet to its parent star. Although a large, terrestrial telescope can provide the angular resolution necessary to visually separate the planet from the star, atmospheric turbulence limits the telescope's performance. In addition, the parent star appears much brighter than the planet. Adaptive optics (AO) can increase a planet's brightness, but they have little effect on residual star glare.

2 Approach

To overcome these difficulties, we have developed a high-speed photon-counting camera that is sensitive to individual optical and infrared photons. This camera, which brings together cryogenic sensing elements (microcalorimeters) and cryogenic digital electronics, will capture a series of images, taking each frame during the short timescale ($\sim$100 ms) when star glare consists of discrete speckles of light. In any given frame, some pixels may have speckles, while others may be speckle-free. The speckles-free pixels can then be combined to build a final image uninterrupted by star glare and atmospheric turbulence.

Since the sensing elements will be operated at very low temperature stage ($\sim$100 mK), it is very important to reduce the heat input to the elements. Multiplex of the signals from each element is the key technology to reduce the heat input, and a photon-counting camera with thousands of pixels cannot be realized without multiplexing. We have focused on this technology, which nobody had ever achieved at the beginning of this project.

Two ways have been proposed to multiplex the signals from each element. First way is to multiplex signals in time-domain [1] which is to switch the sensing elements to be read out by turns. This method requires fast switches at the very low temperature stage which increases the complicity of the electronics at the cold stage.

The other way is to multiplex signals in frequency-domain [2][3]. This is to bias a sensor with alternating currents instead of a conventional direct current. With an AC biasing, output signal of a sensing element is amplitude modulated by the bias frequency. This enables to sum the signals from several sensors by applying AC biases which are well separated in frequency-domain. With frequency-domain multiplexing, the only additional component required at very low temperature stage is an LC filter to eliminate the noise from other pixels.

Because it is possible to keep the sensor stage electronics simple, we adopted the frequency-domain multiplexing for our cryogenic photon-counting camera.

3 Technical Accomplishments

Since a sensing element with faster decay time requires wider bandwidth with frequency-domain multiplexing, we first developed the read out electronics with our cryogenic X-ray spectrometers [5], then much slower γ-ray spectrometers [4]. Typical decay time of the γ-ray sensors is the order of 1 ms and a sensor requires a bandwidth of the order of 10 kHz in frequency domain, which is reasonably narrow compared to the bandwidth of the cryogenic amplifier we have.

With a summing-loop developed by U. C. Berkeley [2], we demonstrated frequency-domain multiplex read out of two γ-ray sensing elements without loosing the resolving power of the sensors [6] [7]. This is the first demonstration to achieve the multiplexing of microcalorimeters without loosing the signal to noise ratio in the world.

While developing the read out electronics, we did an extensive analysis of the performance of cryogenic sensors [8]. This enables optimization of the performance of the sensing elements.

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